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POSSIBLE USES FOR PHILLIPS LABORATORY MHD GENERATOR

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Final Report

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14. Abstract There is interest in electromagnetic energy sources for applications to directed-energy weapons. Candidates include portable conventional rotating machinery electric generators, magnetic flux compression generators (aka explosive generators, magnetocumulative generators or MCGs) based on explosive action, and magnetohydrodynamic (MHD) generators using chemical energy of explosives or rocket propellants. For portable high-energy MHD generators, US technology base appeared to need rescue. The US has received a MHD device in the PAMIR-3U, developed in the former Soviet Union. The present discussion considers uses of this generator for programs on high-power microwave systems and other directed energy concepts. Future applications will be limited by development and funding of specific technical needs. A useful next step would be detailed design of a system to charge high-voltage pulsers. This design should include comparison of single-pulse switching to achieve high-voltage from an inductive storage coil (energy storage option) vs repetitive switching at low voltage, followed by custom-built transformers (direct-drive option).

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POSSIBLE USES FOR
PHILLIPS LABORATORY MHD GENERATOR

INTRODUCTION

There has been continued interest in sources of electromagnetic energy for potential applications in directed-energy weapons. Candidate sources include portable versions of conventional electric-generators based on rotating machinery, magnetic-flux compression generators (aka, explosive generators, magnetocumulative generators or MCGs) based on explosive action, and magnetohydrodynamic (MHD) generators using chemical energy of explosives or rocket propellants. A principal difficulty with MCG and MHD technologies is their limited usefulness apart from possible, future military applications. The commercial sector has not had sufficient requirement for the special capabilities of high energy, very high power-density generators to sustain their availability and development. It has been necessary, therefore, over the last few decades, to maintain technology options through government sponsorship of research, development and testing, while specific applications develop. In the case of portable, high energy, MHD generators, it appeared, a few years ago, that the technology-base within the US needed to be rescued. The mechanism for this rescue was procurement of a sample MHD generator along with training of government personnel in its operation. The actual device that has been received and tested is the PAMIR-3U, developed in the former Soviet Union. The present discussion considers some possible uses of this generator that may be of interest for programs on high-power microwave systems and other directed-energy concepts.

GENERAL CONSIDERATIONS

Technical discussion of MHD generator operation is briefly discussed in Appendix I. Typical performance data for the PAMIR-3U generator in tests with resistive loads are displayed in Table I and Figures 1 and 2. The average output power of this system is 12 to 14 MW, with a load current of 20 to 28 kA and output voltage of approximately 0.5 kV. These results were obtained with a resistive load-impedance of about 20 mohms. For an output pulse duration of 6 to 10 seconds, the energy delivered to a resistive load exceeds 60 MJ. With such powers and energies available from an existing system owned by the USAF Phillips Laboratory, it is appropriate to consider uses that would benefit present and near term programs.

Possible uses divide into two categories: 1) applications that require higher power than the basic output power of the generator, and, therefore, involve intermediate energy storage, and 2) applications that can use the generator power directly. The first category may include a variety of single-burst, directed-energy concepts, and also simulation of steady or quasi-steady operation at very high powers. The energy stored would be approximately half the product of the average power and the generator output duration. The second category comprises devices that operate at the average power of the generator, either directly or in repetitive pulses, with each pulse involving only a small fraction of the total energy output of the generator. Examples of applications in the first category are electrically-driven projectiles, EMP weapons, single-pulse HPM jammers and endoatmospheric plasma jets. Also, there may be simulations of power conditioning for very high power loads. Examples in the second category are bursts of inductively-switched, high voltage pulses to simulate repetitive pulsing at high average power, megawatt-level tests of plasma jet propagation, and charging of intermediate, capacitive energy stores. This last example represents application of the generator as a portable power source for charging high-voltage pulsers at sites without adequate utility power.

Apart from the details of individual applications, an important difference between the two categories is the size and cost of components to be driven by the generator. An energy store

TABLE I

RANGE OF VALUES FOR PAMIR-3U MHD GENERATOR

(From D.W. Price, et al, "PAMIR-3U Magnetohydrodynamic Generator Results", 10th IEEE Pulsed Power Conference, Albuquerque, NM, 10-13 July 1995)

Average power 10.2 - 14 MW ,	Pulse duration 10.4 - 6.2 sec
Ballast resistance 12 - 23 mohm ,	Load resistance 15 - 25 mohm
Load voltage 0.3 - 0.5 kV ,	Load current 24 - 28 kA

capable of handling the output energy of the generator (~ 60 MJ) will be a significant capital expense. The size and weight of such a store will also demand attention before, during and after its use with the generator. Repetitive switching for other applications, however, involves smaller components, but possibly in large numbers, particularly for devices that are partially or completely destroyed by their operation, (e.g., explosively-driven current-interrupters). In any event, it is unlikely that use of the present generator will be possible with apparatus that represents useful application of high power-density technology without incurring significant expenses beyond operation of the generator itself.

CONSIDERATIONS OF ENERGY-STORAGE OPTION

For the category of applications in which powers much higher than the basic output power of the generator are needed, (e.g., GW vs MW), an intermediate energy store is required. Traditionally, at multi-megajoule levels of energy storage, inductive vs capacitive stores are favored in terms of size and cost. The most straightforward approach to storing the total energy output of the generator would be a multi-turn coil. The present section considers the preliminary design of such a coil in order to estimate the cost and other resources needed to pursue options requiring intermediate storage of the total generator output.

If the generator is considered simply as a constant voltage source, the current in an inductive-storage coil will increase as:

$$J/J_O = (1 - e^{-\tau}) \qquad (1)$$

where $\tau = t V_O / LJ_O$ is a normalized time variable, based on the coil inductance, L , the output voltage V_O, and the characteristic current, $J_O = V_O / R$ for constant coil resistance R. In this situation, the output current from the generator and the associated rate at which work is extracted from the propellant flow both increase with time. The values of inductance and resistance of the coil are therefore specified to allow the current to achieve its maximum permitted value, $J = J_m$, only at the end of the generator run. (Appendix II considers an alternative arrangement that would maintain nearly constant output current during the generator run in order to approximate previous tests of the generator with purely resistive loads.)

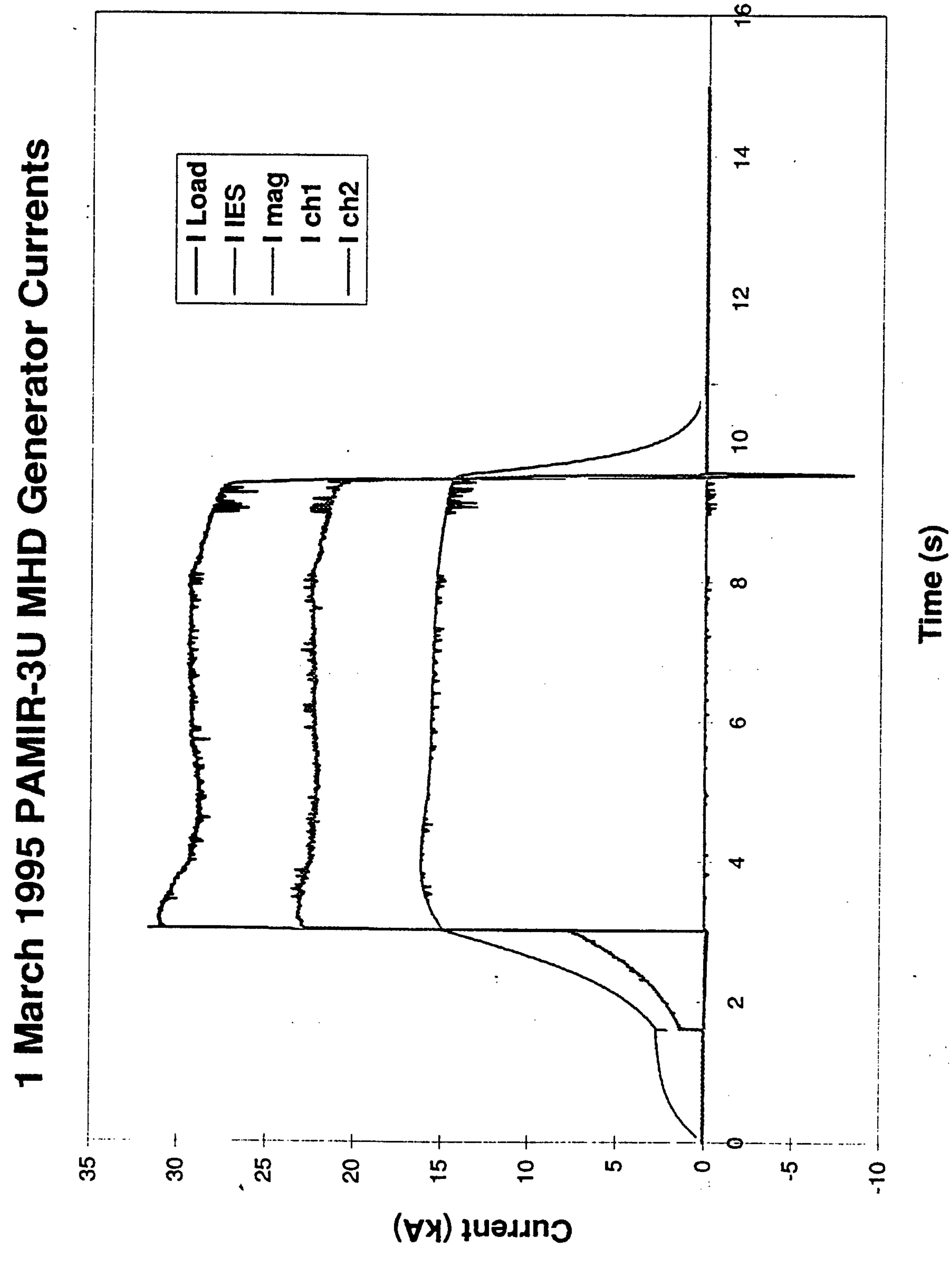


Figure 1 : Currents in PAMIR-3U MHD Generator System, 1 March 1995, (See Appendix I, Figure A.I.2 for circuit nomenclature)

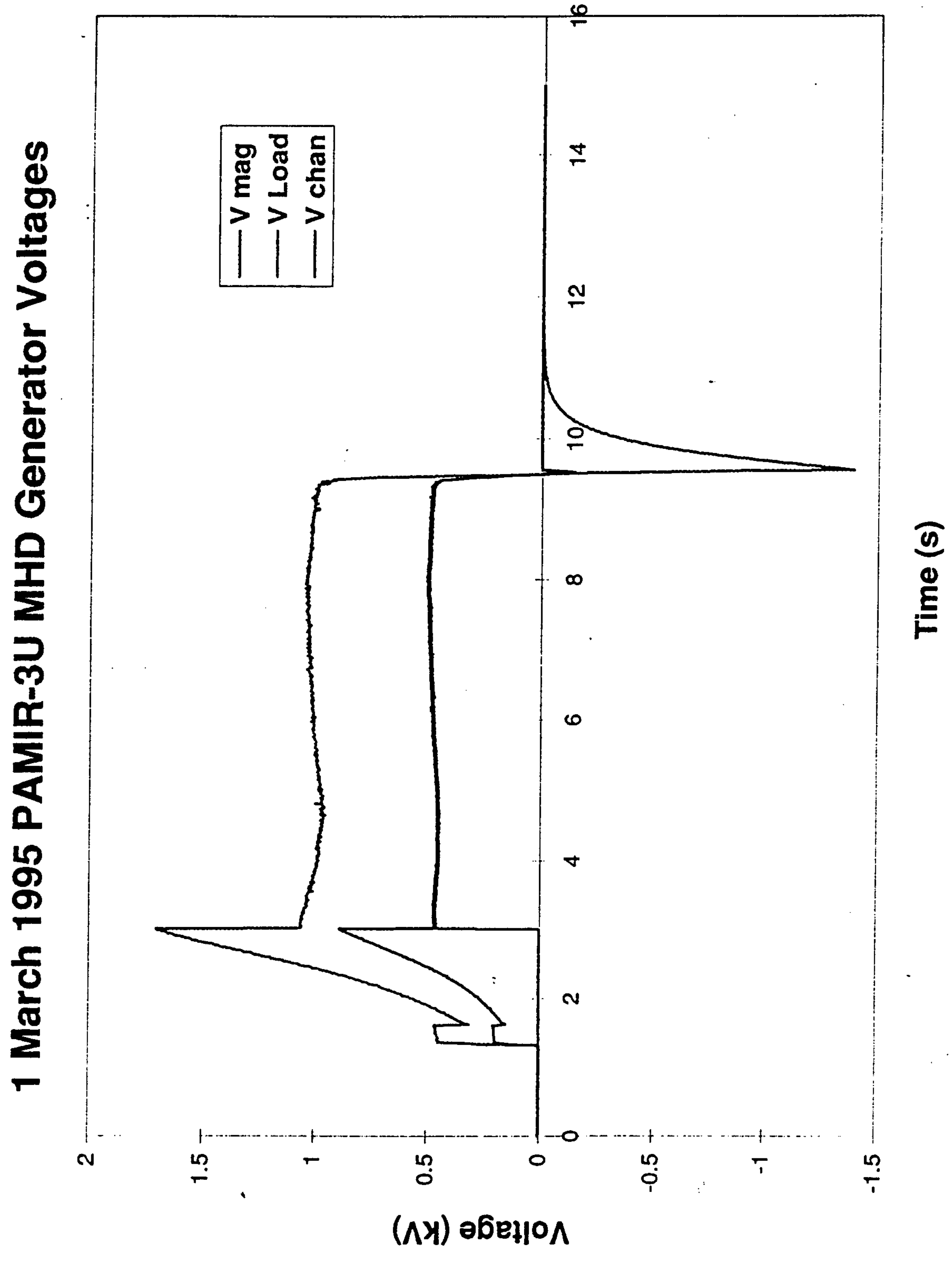


Figure 2 : Voltages in PAMIR-3U MHD Generator System, 1 March 1995, (See Appendix I, Figure A.I.2 for circuit nomenclature)

The energy stored in the inductor at the end of the generator run ($t = t_g$) is simply:

$$W = LJ_m^2 / 2$$

$$= V_o J_m t_g \left(1 - e^{-\tau} \right) / 2\tau \qquad (2)$$

At fixed value of $t = t_g$, the energy stored maximizes for $\tau = 0$, corresponding to a coil resistance of zero. The cost of approaching this condition is directly related to the size and weight of the storage coil, so optimization is usually based on a the energy per unit mass (or cost) of the coil.

The inductance and resistance of the storage coil both depend on the size and geometry of the coil, the number of turns, and the conducting material. The inductance of a solenoidal coil may be written as:

$$L = \mu\pi N^2 r^2 K_L / h \qquad (3)$$

where N is the number of turns, r and h are the inner radius and length of the coil, respectively, and K_L is a correction factor for coils with finite length-to-diameter ratio and thickness . For a Brooks coil, which provides the maximum inductance for a given length of wire, the coil radius, length and thickness all have the same value, x, so the inductance is:

$$L = K_{LB} \mu\pi N^2 x \qquad (4)$$

where the value for the correction factor, K_{LB}, is approximately 0.65. The associated resistance for a wound-coil, with uniform current density in the windings, is:

$$R = \eta z / A_i \qquad (5)$$

where η is the electrical resistivity, A_i is the cross-sectional area of a turn of wire, and z is the total length of wire. The N turns of wire, including insulation and spacing, use the available cross-sectional area, x^2, and the volume of the coil is $3\pi x^3$. The wire length is, therefore:

$$z = 3\pi Nx \qquad (6)$$

Only a fraction, f, of the cross-section is conducting material, so:

$$A_i = f x^2 / N \qquad (7)$$

The coil resistance is then:

$$R = 3\pi\eta N^2 / f x \qquad (8)$$

The characteristic time (for current decay) is:

$$L / R = (K_{LB}\, f / 3)\,(\mu / \eta)\, x^2 \tag{9}$$

The size and mass of the coil are, therefore, directly related to the value of the normalized-time at the end of the generator run, $\tau = R\, t_g / L$. The mass of conductor, for example, is:

$$\begin{aligned} M &= \rho\,(3\pi x^3)\, f \\ &= 3\pi\rho\,[(3 / K_{LB})(\eta / \mu)(t_g / \tau)]^{3/2} / f^{1/2} \end{aligned} \tag{10}$$

where ρ is the mass density of the conductor. This mass may be divided into the energy stored by the coil (Eqn. (2)) to obtain the energy per unit mass

$$W/M = \{V_o J_m\, f^{1/2} / 6\, t_g^{1/2}\, \pi\rho\,[(3 / K_{LB})(\eta / \mu)]^{3/2}\}\, \tau^{1/2}(1 - e^{-\tau}) \tag{11}$$

The functional variations with respect to $\tau = R\, t_g / L$ of the coil energy and energy per unit mass are displayed in Figure 3. Note that higher values of coil-energy require higher values of coil mass, so a design trade-off is needed. A reasonable value for normalized- time is $\tau = 2$, for which the energy of the coil would be 43% of its maximum value ($\tau = 0$), and the relative gains available for the energy per unit mass have begun to diminish.

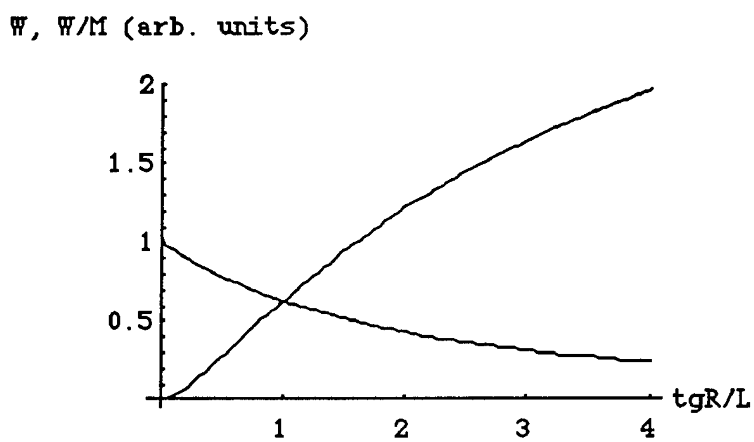


Figure 3: Coil-energy, W, and energy per unit mass, W / M, are decreasing and increasing functions, respectively, of normalized-time at the end of the generator run, $\tau = R\, t_g / L$

As a sample design, suppose that the generator output duration is $t_g = 6.2$ sec, by which time the constant output voltage $V_o = 0.5$ kV has created a maximum current $J_m = 28$ kA in the storage coil. With $\tau = 2$, the L/R-time of the coil is 3.1 sec, so Eqn. (9) provides the coil dimension, x , for assumed values of electrical resistivity and areal efficiency. For $\eta = 1.72 \times 10^{-8}$ ohm-m (copper), and f = 0.8, then x = 0.5 m; the mass of copper is M = 8.17 tonnes.

From Eqn. (2), the energy stored in the coil is 18.8 MJ, which, at 28 kA, means that the coil inductance is L = 0.048 henries. The number of turns required for the assumed Brooks-coil to provide this inductance is then N = 194; fourteen layers of fourteen turns along the length of the coil is a reasonable approximation. For N = 196, the diameter of the copper would be 3.6 cm (1.4 inches). This size suggests insulated, multi-strand cable as the basic material for coil fabrication. (Cautionary note: connection of pairs of separately-insulated cables in the 100 MJ inductive store for the Tunnel F power system at Arnold Engineering Development Center resulted in unexpected forces during current interruption.) The present coil would have a magnetic field on the centerline of about 4.6 T, and effective pressures at the coil of about 500 atm. The energy per unit mass (of copper) is 2.3 kJ/kg.

A lighter, but larger, inductive energy-store could be manufactured using a roll of thin aluminum sheet, with Mylar film insulating the turns of a spirally-wound coil. In this case, K_L = 0.52 , but a larger areal efficiency is possible (say, f = 0.9). The electrical resistivity, however, is higher for aluminum (2.7 x 10^{-8} ohm-m) vs copper. The resulting coil has a 32% larger value for the characteristic dimension, x = 0.65 m. The necessary inductance is the same as before, and the number of turns is slightly less, N = 189. The thickness of the aluminum sheet is then 3.1 mm (about one-eighth inch), which leaves about 0.34 mm (13.6 mils) for insulation. The length of the aluminum sheet is 1165 m, and represents a mass of 6.4 tonnes. At an approximate price of $ 2.50 per pound, the aluminum for the coil would cost 35.2 k$. The energy per unit mass of this alternative design is 2.9 kJ/kg.

Interruption of current flow by a switch in series with the inductor would provide a high-voltage pulse that could be used to drive a load or to charge a capacitor bank for subsequent use in driving high-voltage loads. In the latter case, the capacitor bank would store only a small fraction of the total energy available from the inductor, but would be repeatedly charged and discharged to provide a train of high-voltage pulses. Such repetitive operation could be useful in demonstrating high average-power, high rep-rate performance of microwave-producing diodes. For the sample designs of the inductor, the overall size and allowable space for insulation should be sufficient to permit interruption of the current at voltages in excess of 0.5 MV. (A single interrupter in the form of the explosively-driven breaker / fuse combination used at the Naval Research Laboratory, c.1979, would be a reasonable choice for switching.) The resulting output pulse provides a high-voltage DC source for charging a relatively small capacitor bank (say, 10 kJ) to drive a diode. With only a single interrupter, the DC source would offer high-voltage for 1 - 2 msec, during which a train of ten to a hundred pulses could be supplied at a 10 -100 kHz rep-rate. Thus, operation at gigawatt-level, average-powers could be simulated.

Gigawatt-level performance at very high currents can be obtained by using the multi-turn inductor as the primary of a current-step-up transformer. This approach has been proposed for the NRL liner implosion program (c. 1974) and also used in the liner implosion and high-field tokamak projects at the Kurchatov Institute of Atomic Energy, Moscow. With ideal coupling, the primary-current of 28 kA could be increased to a single-turn, secondary-current of 5.4 MA. Such a current level, for the millisecond pulsetime associated with interruption of the primary-current at 0.5 - 1 MV, is useful for electromagnetic acceleration of projectiles, implosion of large, relatively slow liners (~ 1 - 2 km/s), and powering very high-energy lasers or plasma jets.

Without recourse to tranformer operation or intermediate capacitive-storage at relatively low energy density, applications are needed with load impedances much greater than the generator output impedance (~ 18 mΩ). Operation as a high-voltage DC source satisfies this criterion. While there may be interest at some time in driving high-impedance plasma discharges employed in some electrically-pumped lasers, most electric guns and arc-discharge devices have impedances in the 1 - 20 mΩ range. Use of the energy-storage option to drive a plasma jet ($Z \simeq 10$ mΩ), for example, is not warranted. It is appropriate, therefore, to consider applications that could benefit from the direct power output of the generator.

CONSIDERATIONS OF DIRECT-DRIVE OPTION

The use of the output power directly from the generator has two forms: 1) steady-state operation of loads with impedances approximating the generator impedance and 2) operation of pulsed loads for which the generator represents a primary source of power that is conditioned by switching, transformers, capacitors and filters. The first form has readily identifiable applications wherever arc discharges are needed at several megawatt power-levels. The second form includes experiments at sites that lack sufficient utility power (and would permit MHD generator operation).

An example of a load involving an arc discharge is the magnetoplasmadynamic (MPD) arcjet. This device is typically envisioned for electric propulsion of space vehicles. At multi-megawatt power-levels, MPD thrusters have been operated in quasi-steady mode in which millisecond pulses of current and energy are supplied from capacitive storage in lumped-element transmission lines. The benefits of very high current operation, (high magnetic fields from the discharge current itself, high electromotive voltages compared to electrode falls), are thereby obtained at average power levels consistent with expected space-based power technology (kW vs MW). Steady-state operation of MPD thrusters at multi-megawatt powers has been proposed for missions to Mars, but does not appear to be required or possible for near term Air Force needs. MPD arcjet techniques, however, may find use for non-propulsion applications in which high energy-density columns of plasma are quickly projected into the atmosphere. These applications could include plasma antennas, infrared-decoys, and endoatmospheric missile defense.

Penetration of dense plasma jets into a surrounding atmosphere that provides radial confinement of the jet has been studied computationally and experimentally. It appears that the range of propagation of the jet is limited by the time of operation of the source, and by the power needed to overcome viscous drag. The first limitation basically recognizes that the head of the jet travels at a constant speed for which the dynamic pressure of the jet balances the dynamic pressure of the atmosphere (in the frame of reference of the head of the jet):

$$p_j + \rho_j (u_j - u_p)^2 = p_a + \rho_a u_p^2 \tag{12}$$

where the subscripts 'j' and 'a' refer, respectively, to the jet flow and atmosphere. The jet flow speed, u_j, and the penetration speed of the head of the jet, u_p, are measured in the laboratory frame. Radial confinement of the jet by the atmosphere means that $p_j = p_a$, so the propagation speed merely depends on the jet speed and the ratio, D, of jet density to atmospheric density:

$$u_p / u_j = D^{1/2} / (1 + D^{1/2}) \tag{13}$$

With $p_j = p_a$, the value of D depends on the molecular weight of the jet material relative to the atmosphere and their relative temperatures:

$$D = (m_j / m_a)(T_a / T_j) \tag{14}$$

For a xenon jet, at $T_j = 10^4$ K, propagating in air at 300 K, D = 0.14, so $u_p / u_j = 0.27$. It is typical for MPD thrusters to exhibit exhaust speeds limited to about three times Alfven critical speed:

$$v_{cr} = (2\, U_i / m_j)^{1/2} \tag{15}$$

where U_i is the ionization energy of the propellant molecule. For xenon, v_{cr} =4200 m/s, so a reasonable value for u_j = 12.6 km/s. The propagation speed of the jet is then 3.4 km/s. Operation of an MPD thruster with the MHD generator output pulsetime of 6.2 sec would permit a range of 21 km.

Friction of the jet with the atmosphere, however, can limit the range to lower values. Basically, the increased size of the boundary layer in the air surrounding the jet reaches the point that more power is spent moving this air than increasing the energy of the jet itself. Calculations based on laminar viscosity for the outer portions of the boundary layer indicate that jet ranges above 10 km would require hundreds of megawatts of source power. At 14 MW, the present MHD generator might still be able to provide a useful experimental test of dense plasma jet propagation. The load impedance, however, with a self-field MPD thruster at 28 kA, will be significantly lower than the generator impedance (~ 4 -6 mΩ vs 18 mΩ). The actual source power, therefore, would be only a few megawatts. This power level is still comparable to previous experimental tests at sub-atmospheric pressures with half-millisecond pulses, driven by capacitive pulselines. Thus, useful experiments could be performed that would extend evaluation of endoatmospheric propagation of dense plasma jets to new regimes.

Apart from the possible use of atmospheric jets for plasma antennas, direct operation of the generator could benefit high-power microwave projects simply as a means for charging high-voltage pulsers. The principal task here is to convert the relatively low-voltage DC output of the generator into high-voltage DC power. Standard electrical engineering technology is available for this requirement. The DC output is changed to AC (full-wave or half-wave) power, which is then converted to high-voltage AC power by means of conventional transformers. This AC power is basically rectified and filtered to provide the appropriate voltage for charging the individual stages of a pulser (e.g., Marx generator).

The main differences between using the MHD generator and utility lines for charging the power are the need for switching to create the low-voltage AC power and for additional levels of transformer action; utility power at multi-megawatt levels is typically available at higher voltages (e.g., 13.4 kV) than the sub-kilovolt values from the present MHD generator. Lower input voltages at high power imply higher currents and, therefore, more massive transformers and components. Silicon-Controlled Rectifier (SCR) technology is adequate to handle the basic switching of the generator output. Present SCRs can operate at hold-off voltages in excess of 2500 V and currents (per switch) above 2500 A. Thus, a dozen SCRs in parallel could provide the main components for converting the DC output to AC power. The cost of such an array would be in the neighborhood of 30 k$.

While the cost of the switching elements is reasonably modest (but non-zero), it would be necessary to employ an electrical engineering (power) specialist to design the circuitry and to evaluate factors such as fault-modes and thermal loadings. Similar talent is required to accomplish the design of the transformers, which, most likely, would have to be customized units. All told, expenses of at least 100 k$ for hardware and an additional 100 k$ for engineering support should be anticipated in developing a system that could convert the MHD generator into a power source for high-voltage pulsers.

SUMMARY REMARKS

Table II summarizes some possible uses for the Phillips Laboratory MHD generator. Both the energy-storage option and the direct-drive option can provide useful capabilities for future Phillips Laboratory projects. In both cases, however, the cost of conditioning the electromagnetic energy provided by the generator can involve 100 to 200 k$, and would require about a year of engineering and procurement time. The one exception would be the use of the generator directly to drive a plasma jet. In this case, the hardware is relatively inexpensive and actually represents the experimental apparatus, rather than power conditioning. (Unfortunately, such an experiment is probably not the highest priority for present missions.) It may be reasonable, during times of constrained budgets, to limit the next step toward use of the MHD generator to detailed design for a system to charge high-voltage pulsers. This design should include comparison of single-pulse switching to achieve high voltage from an inductive storage coil (energy-storage option) vs repetitive switching at low voltage, followed by custom-built transformers (direct-drive option). There would be a need to wrap large, multi-turn coils in either approach. The former case involves straightforward, albeit non-standard engineering design, but allows other possibilities for using a large amount of energy in a single pulse or very high-power train of pulses. The direct-drive option is standard power engineering, but only provides a substitute for utility power coupled to commercially-available, high-voltage power supplies. The possible importance of such capability for operation at remote sites is beyond further consideration here.

In any event, it appears that the primary goal of preserving a potentially useful technology has been accomplished by the successful procurement and operation of a high power MHD generator by the Phillips Laboratory. This goal recognized that future applications would be limited by development and funding of specific technical needs. In the near term, at least, these limitations will continue to prevail and cannot be ignored in planning further tests with the present generator.

TABLE II

SUMMARY OF PHILLIPS LABORATORY MHD GENERATOR USES

ENERGY-STORAGE OPTION :

Energy -- 18.8 MJ , (Primary) Current -- 28 kA , Output Voltage -- 0.5 MV

Pulsetime -- 2 msec , (Single-turn, Secondary) Current -- 5.4 MA

Applications:

High-voltage power source for high average-power diode pulsers

High-current, millisecond pulses for electric guns, plasma jets, lasers

DIRECT-DRIVE OPTION :

Average Power 14 MW , Output Current -- 28 kA , Output Voltage -- 0.5 kV

Pulse Duration -- 6.3 sec , Impedance -- ~ 20 mΩ

Applications:

High-power source to substitute for utility power at remote-sites

Power source for megawatt-level tests of plasma jet propagation

APPENDIX I

TECHNICAL BACKGROUND

The basic operation of an MHD generator comprises a high-speed flow of electrically conducting material, a magnetic field that penetrates this flow, and an arrangement of electrodes that will allow current to cross the magnetic field and flow in response to the electric field developed in the flow. There are many variations on the basic concept of an MHD generator, ranging from a solid-conductor disc, rotating in a magnetic field (usually termed a Faraday dynamo or homopolar generator) to plasma flows in multi-electrode channels. Moving conductors are, of course, also used in other types of generators, such as magnetocumulative generators (MCGs).

In general, the distinction between MHD generators and MCGs can be made in terms of the magnetic Reynolds number, $R_m = \sigma\mu u L$, where σ is the electrical conductivity of the flow (equal to the inverse of the electrical resistivity, η), μ is the permeability of the flow, (usually equal to $4\pi \times 10^{-7}$ h/m in MKSA units), u is the flow speed and L is a characteristic dimension of the flow, such as the channel diameter. The magnetic Reynolds number compares the tendency of the flow to convect magnetic flux with the tendency of flux to diffuse through the conductor (and establish a distribution of current density in accord with the conductivity of the flow and the electrode spacing). In MCGs, $R_m >> 1$, so magnetic flux can be compressed, thereby converting kinetic energy of the conductor into electromagnetic energy. For MHD generators, in the form of linear (vs rotating) flows, $R_m < 1$, so the entire flow tends to be penetrated by magnetic field, $\mathbf{B}$. The current density, $\mathbf{j}$, is distributed through the flow (and on electrode surfaces), so the Lorentz force ($\mathbf{j} \times \mathbf{B}$) acts to oppose the momentum everywhere in the flow. (In the case of rotating flows, as in homopolar generators, the axisymmetry of the flow and magnetic-field distributions permits fully-diffused operation even though R_m can be much greater than unity. Radial current-flow in the disc interacts with the axial magnetic-field to create a torque that opposes the rotational motion.)

An MHD generator can provide a steady source of voltage as long as the conditions of flow speed and magnetic field are maintained. The conductivity of the flow basically determines the extent to which electromagnetic energy, generated by the Lorentz force working against the flow, is converted locally into heat by resistive dissipation or is available to power an external load. The generation of electromagnetic power (per unit volume) is $- \mathbf{E} \cdot \mathbf{j}$, where the electric field in the flow is given by a generalized Ohm's law:

$$\mathbf{E} = \eta\, \mathbf{j} - \mathbf{u}_e \times \mathbf{B} \qquad \text{(A.I.1)}$$

The electron flow velocity $\mathbf{u}_e$ is used for generality here because it includes the Hall effect found in MHD generator flows at low density. Often, the flow density and degree of ionization are sufficiently high to allow replacement of $\mathbf{u}_e$ by the flow velocity $\mathbf{u}$. The density of power generation is then:

$$P_g = \mathbf{j} \cdot (\mathbf{u} \times \mathbf{B}) - \eta\, \mathbf{j}^2$$

$$= -\mathbf{u} \cdot (\mathbf{j} \times \mathbf{B}) - \eta\, \mathbf{j}^2 \qquad \text{(A.I.2)}$$

where the first term on the right represents the Lorentz force working against the flow, and the second term is the power deposited in the flow by resistive heating.

A sketch of an MHD generator is provided in Figure A.I.1, along with a load circuit. Note that current flow through a load in response to the generator voltage results in current flow through the generator in a direction opposite to the electric field in the channel. The resistance in the generator is electrically in series with the load. Maximum power transfer to the load, therefore, occurs when the load impedance matches the internal impedance of the generator.

The magnetic field of the generator requires a source of power that could be an external supply, such as batteries. Often, an initial amount of energy is supplied by an external source, but the main energy for the magnet is provided by the generator itself. Such self-excited operation capitalizes on the high power and energy density available with MHD technology. When the magnetic field has reached the value needed for the desired output voltage, closure of a switch connects the load in parallel with the magnet circuit. (Reduction of the voltage driving the magnet is necessary to maintain the magnetic-field value for constant power operation of the load.) Figure A.I.2 shows the circuit diagram of the PAMIR-3U system, which incorporates an initial excitation source and self-excitation.

SCHEMATIC ARRANGEMENT OF MHD GENERATOR

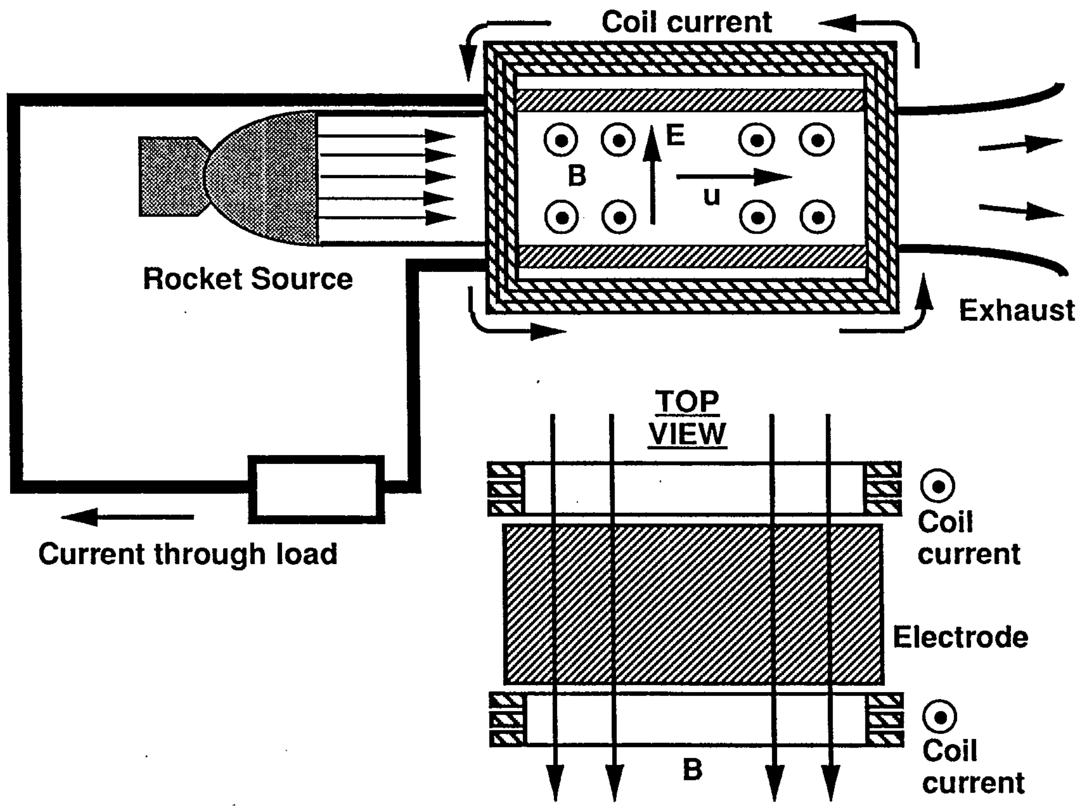
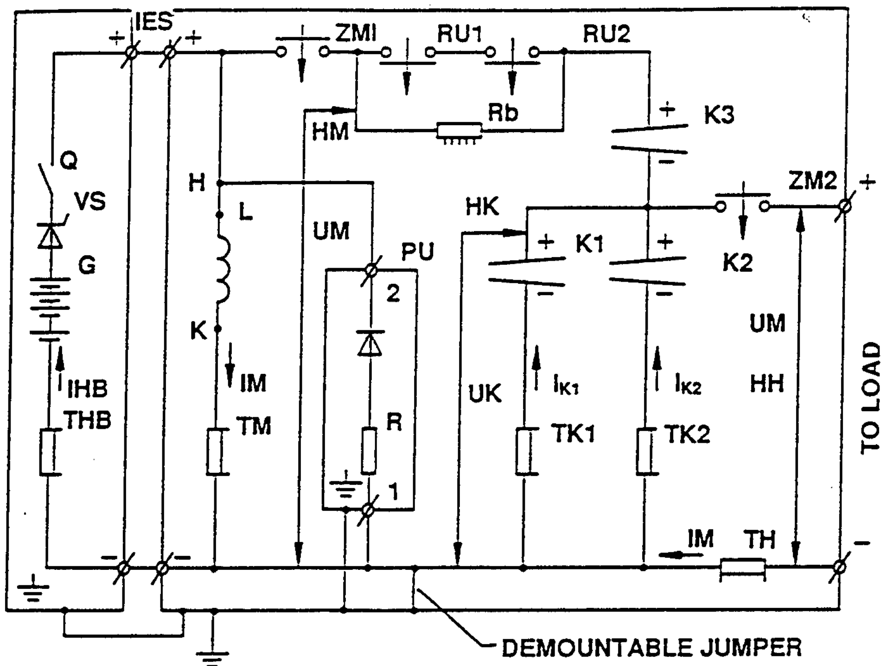


FIGURE A.I.1



TM, TK1, TK2, TH, THB-CURRENT TRANSDUCERS

HM, HK, HH - CONNECTION POINTS OF VOLTAGE TRANSDUCERS

DESIG-NATION	NAME	NUM-BER	NOTE
IES	INITIAL EXCITATION SYSTEM		
	IM1 - 3.03.00.000	1	
K1 to K3	UNIT IM - 112-5.00.000	3	MHD CHANNEL
L	MAGNET SYSTEM IM1-3.01.10.000	1	
RU1, RU2	BREAKER IM - 115-VP-1.00.000	2	
ZM1, ZM2	CONTACTOR X-8F 01.05.000	2	
PU	PROTECTION UNIT IM1 -3.02.00.500	1	R = 0.1Ω
R6	BALLAST RESISTANCE		
	IM1 - 051M.01.05.000	1	R_{MAX} = 40 mΩ

Figure A.I.2 : Circuit for PAMIR-3U MHD Generator, (from D.W. Swallom, J.S. Gibbs, I. Sadovnik, "PAMIR-3U Systems and Subsystems Analysis", June 1995, Contract No. F29601-93-C-0033)

APPENDIX II

EXAMPLE OF ENERGY-STORAGE OPTION WITH CONTROLLED LOAD-IMPEDANCE

In order to energize the inductive store while maintaining constant output voltage and current from the generator, it is necessary to include some active elements in the circuit. These elements could be switches, capacitors, reactors and filters. For purposes here, suppose that a variable resistor, $R_p(t)$, is included in parallel with the load inductance, L, (and its resistance, R). If the voltage output of the generator is held constant at V_o, (by control of the magnetic current), the current in the inductive store will increase with time as:

$$J / J_o = (1 - e^{-r\tau}) / r \qquad \text{(A.II.1)}$$

where $\tau = t V_o / LJ_o$ is a normalized time variable, r is the ratio of resistance R to the initial value of the parallel resistor, $R_p(0) = R_o$, and the characteristic current, J_o , is the initial output current, V_o / R_o.

The necessary increase of the parallel resistance may be obtained simply, if some variation of the output current of the generator is allowed. Joule heating increases resistance as energy, W_p, is deposited in the conductor:

$$R_p(t) = R_o [1 + \beta_v W_p(t)] \qquad \text{(A.II.2)}$$

where β_v is a constant of the conductor, divided by the volume of conducting material. The rate of heat deposition is:

$$dW_p(t) /dt = V_o^2 / R_p(t)$$

$$= V_o^2 / R_o [1 + \beta_v W_p(t)] \qquad \text{(A.II.3)}$$

Solution of this equation gives:

$$R_p(t) / R_o = [1 + 2 \beta_v V_o^2 t / R_o]^{1/2} \qquad \text{(A.II.4)}$$

In terms of the normalized time, $\tau = t V_o / LJ_o$, the current through the parallel resistor is:

$$J_p / J_o = 1 / [1 + 2 \beta_v LJ_o^2 \tau]^{1/2} \qquad \text{(A.II.5)}$$

The total current from the generator is the sum of this current and the current in the inductive store from Eqn. (A.II.1):

$$J_T / J_o = 1 / [1 + 2 \beta_v LJ_o^2 \tau]^{1/2} + (1 - e^{-r\tau}) / r \qquad \text{(A.II.6)}$$

Figure A.II.1 displays the variation of total current with time for r = 0.7, and $2\beta_V L J_o^2 = 10$. These parameters permit the current to exhibit excursions of about 20% from the initial current from the generator (to the parallel resistor). By $\tau = 1.5$, the value of the parallel resistance increases a factor of four because of Joule heating. This increase is possible without disrupting the material, so non-destructive, repeated operation of the parallel resistor should be possible.

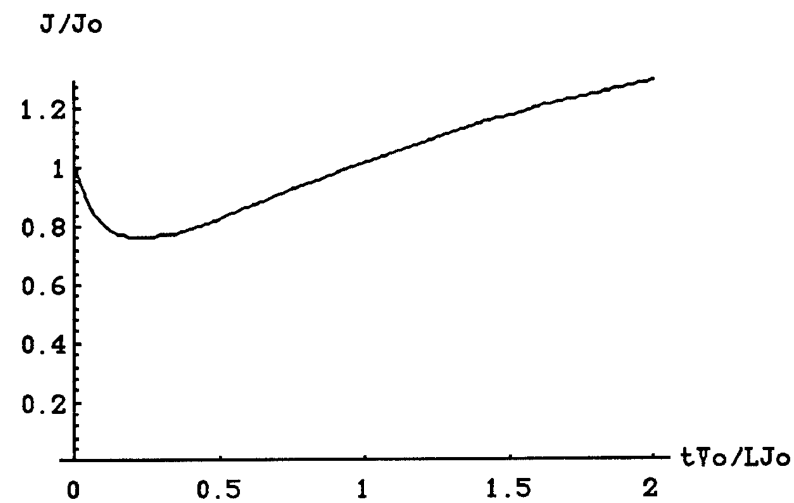


Figure A.II.1: Output current relative to initial current J_o vs normalized time τ, (with r = 0.7)

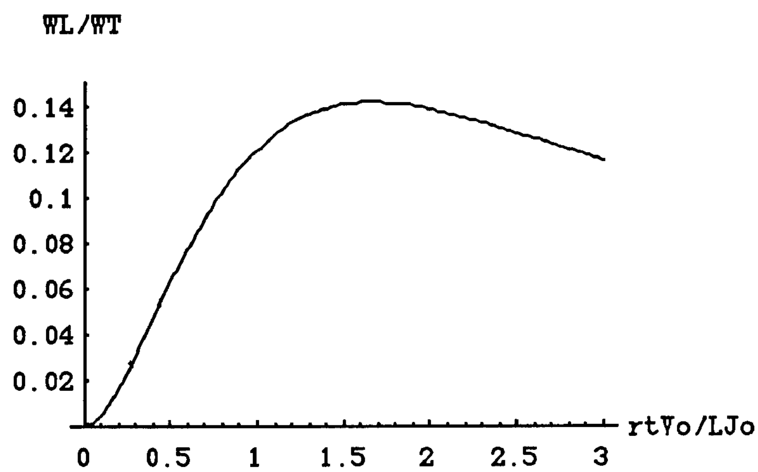


Figure A.II.2: Stored energy relative to output energy vs time normalized by L/R, with r= 0.7 and factor of four increase of parallel resistance.

For the parameters of this example, the current in the inductor (at $\tau = 1.5$) is 0.929 J_o, and the energy stored is about 13% of the total energy delivered to the parallel resistor and the storage coil. Figure A.II.2 displays the energy delivered to the inductive store relative to the total output energy as a function of $r\tau$, for $r = R / R_p(0)$ of 0.7 and a factor of four increase in the value of the parallel resistance during the output pulse. It appears that only a very slight increase of stored energy might be possible, if current excursions are limited to the nominal 20% assumed here. Note that, when the generator is operated as a voltage source simply feeding the inductive store, without any series or parallel resistance, the efficiency of utilizing the propellant power is poor when the output current is low. Operation with nearly constant current uses the flow power at uniform efficiency, but converts most of this power into heating the resistors that control current excursions. Thus, as long as the generator flow can tolerate a substantial increase in the rate at which work is extracted, it is more efficient to allow the output current to rise from zero to the maximum current value during the output pulsetime of the generator.

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